Cosmology Teach-In / July 3, 13 700 002 003 ABB

Polarization of the Cosmic Microwave Background Radiation

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Outline

- A photon's journey through the universe
- The CMB Power Spectrum
- Polarization at the surface of last scattering
- Primordial Polarization from Inflationary Gravitational Wave Background
  - secondaries: grav. lensing
- Experiments for polarization
  - road to measuring gravity wave signal

Our Habitat

"my first reaction to cosmology was one of surprise that grown people could seriously care about such a schematic physical theory." (Peebles)

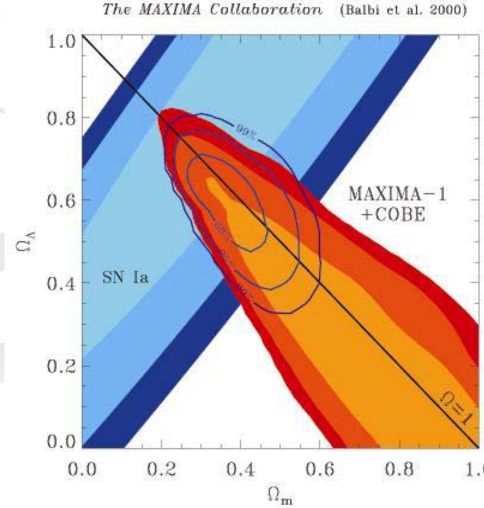
CMB temperature anisotropy measurements of the acoustic peaks (+SN1a) have revolutionized our self image

speculative cosmology has evolved into our cosmological model

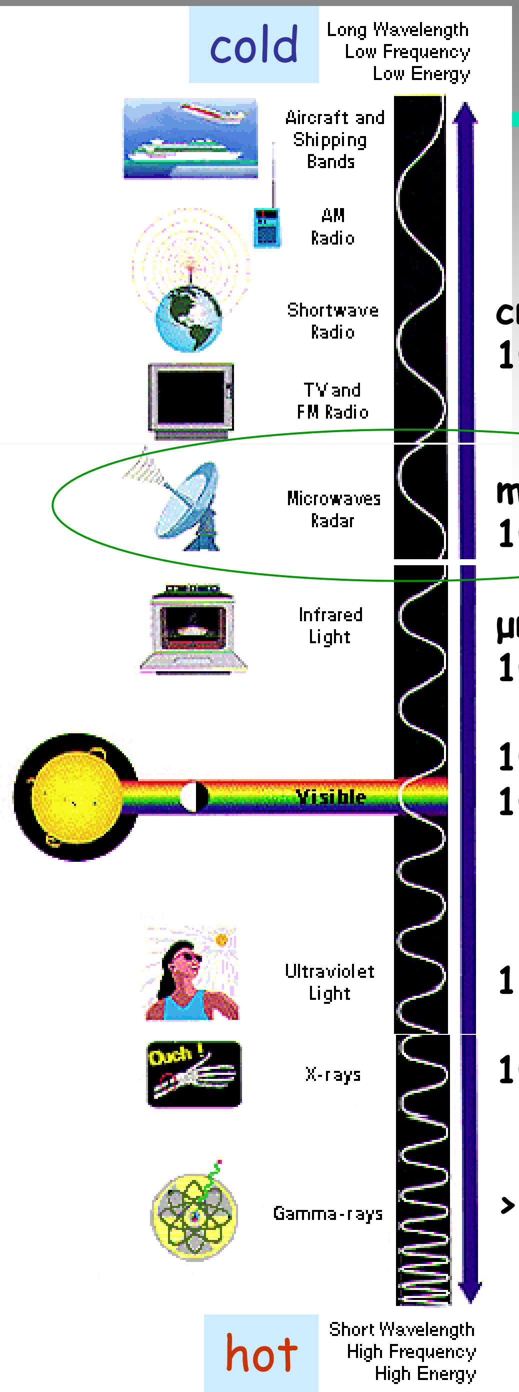
- we live in a spatially flat (critically dense) $\Omega_{tot}=1$ universe
- consisting mainly (95%) of dark matter and dark energy
- in which structure arises through *gravitational instability* from quantum fluctuations during an inflationary epoch.

a ***"Cosmic Concordance"*** has emerged.

The MAXIMA Collaboration (Balbi et al. 2000)



The Electromagnetic Spectrum



cm→km
10^{-2}–10^{3} m

"CMB" photons in the future.

mm→cm
10^{-3}–10^{-2} m

CMB Photons Now

μm
10^{-6}–10^{-4} m

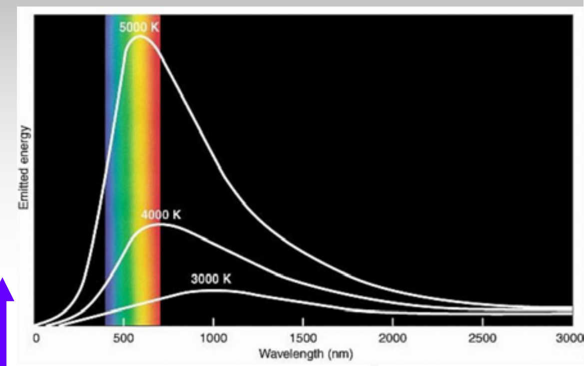
100s nm
10^{-7}–10^{-6} m

1–10^{2} eV

10^{2}–10^{5} eV

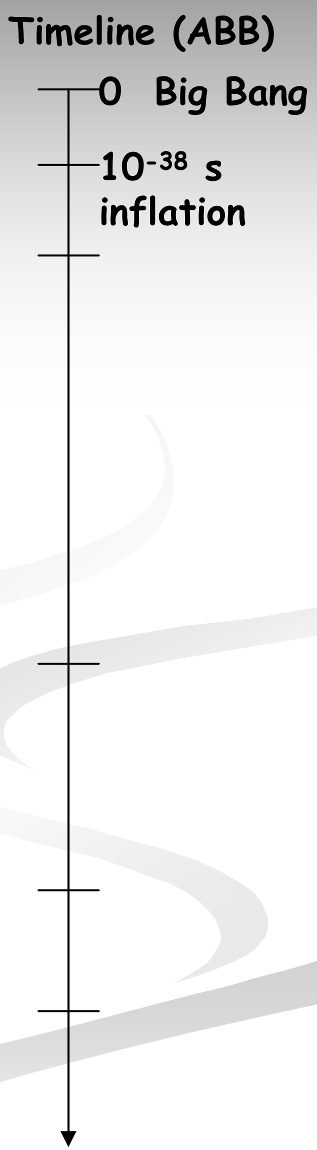
>10^{5} eV

"CMB" photons a long time ago.



as the universe expands & cools, the Cosmic Background Radiation photons are stretched, and evolve through the EM spectrum.

Life of a Cosmic Photon



Inflation

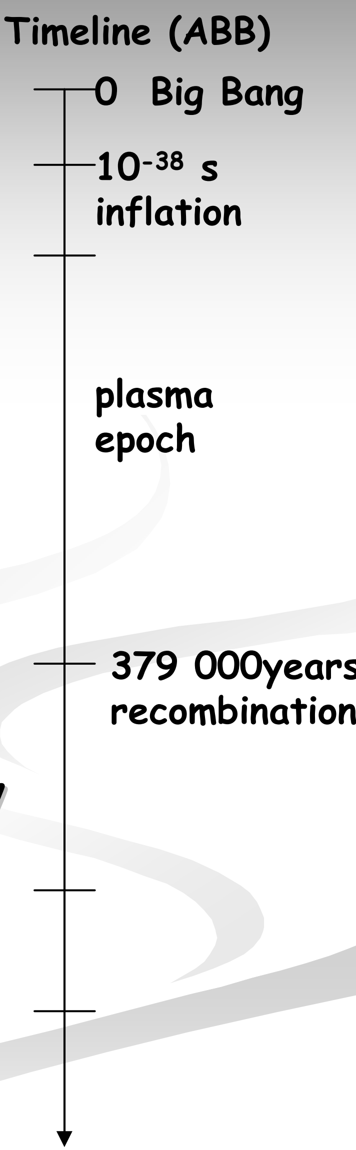
- at t~10^{-38} s ABB, the universe undergoes a phase transition causing an explosive e^{60} exponential expansion
- leaves its imprint as ***inflationary gravitational wave background*** (IGB)
  - → to be **encoded on the CMB** at the surface of last scattering as a curl (***B-mode***) component to the polarization

- inflation provides answers for:
  - horizon problem: explains why CMB is isotropic on cosmically unconnected scales >= 1-2°
  - flatness problem (Ω=1): exponential expansion locally flattens spatial curvature to high precision.
  - predicts scale invariant adiabatic density perturbations

Life of a Cosmic Photon

Plasma Epoch

- density perturbations undergo gravitationally driven ***acoustic oscillations***.
  - gravitational wells from matter over-densities cause the plasma to fall inwards
  - until eventually it rebounds under radiation pressure.
- matter and radiation are ***tightly coupled***
  - information about matter distributions are precisely encoded in radiation



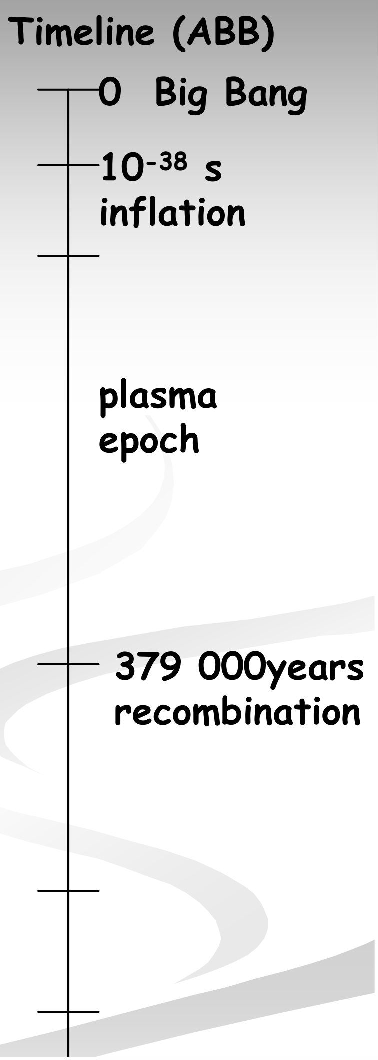
Life of a Cosmic Photon

t<~400 000 years

- matter and radiation are ***tightly coupled***
  - electrons are Coulomb interaction coupled to baryons
  - photons ***Thomson scatter*** off electrons
    - mean free path λ_C=2.5 Mpc (short!)
    - the universe is ***opaque*** on cosmological scales.

Recombination t~379 000 years ABB z~1089±1 T=3000K

- protons combined with electrons to form neutral hydrogen
  - recombination is sudden, Δz~195±2.
- this is the "surface of last scattering" for most photons– which travel unhindered to us, providing a snap-shot of the universe at time=379Kyears.



Life of a Cosmic Photon

Timeline (ABB)

0 Big Bang

10^{-38} s inflation

Large Scale Structure Formation Epoch

- Matter collapses under gravity to form the rich structure (including us!) of the universe.

- Why the difference between Matter & Radiation now??
  - matter and radiation had the same distribution a few•10^5 years ABB, why not now?

  → *radiation pressure* resists the pull of gravity.
  - this is calculationally important!, because the perturbations in the uniform photon distribution are small, ***linear perturbation theory* applies** and we can calculate things.
  - CMB observations are important not just because they carry a lot of information… but also because ***they are theoretically easy (robust) to predict***.

    (analogy between EW & QCD).

Life of a Cosmic Photon

Timeline (ABB)

0 Big Bang

10^{-35} s
inflation

plasma
epoch

400 000yr
recombination

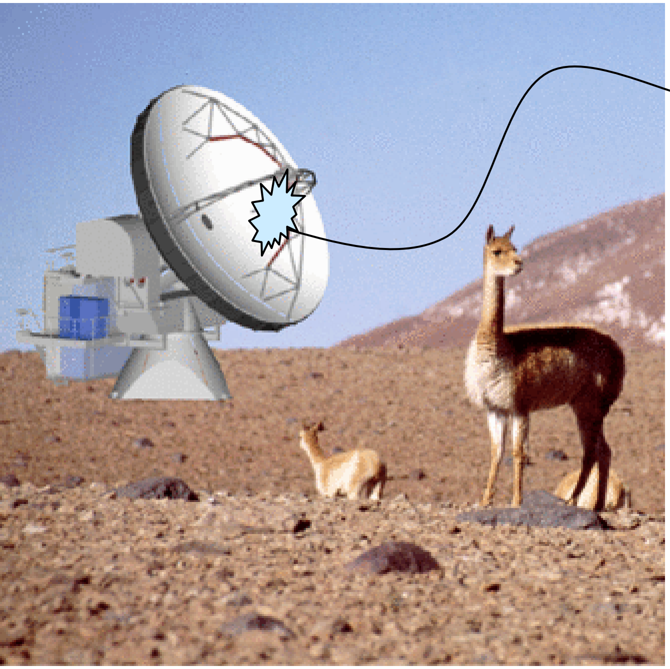
LSS
epoch

180 Myears
z~20
Reionization

14.5 Gyears
NOW

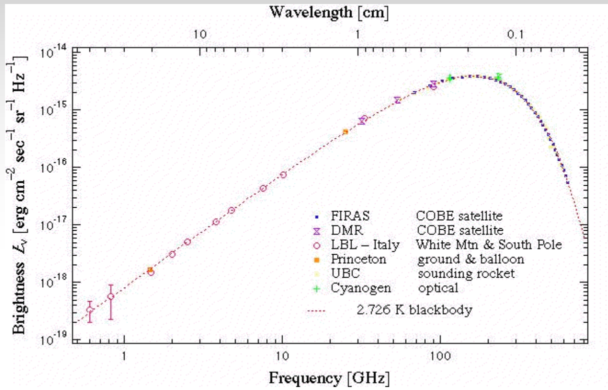
NOW

- t~13 700 002 003 years ABB
- T=2.7 K



End of the line for a precious few of the photons, as we trap them in our detectors and glean a little information about the universe we live in.

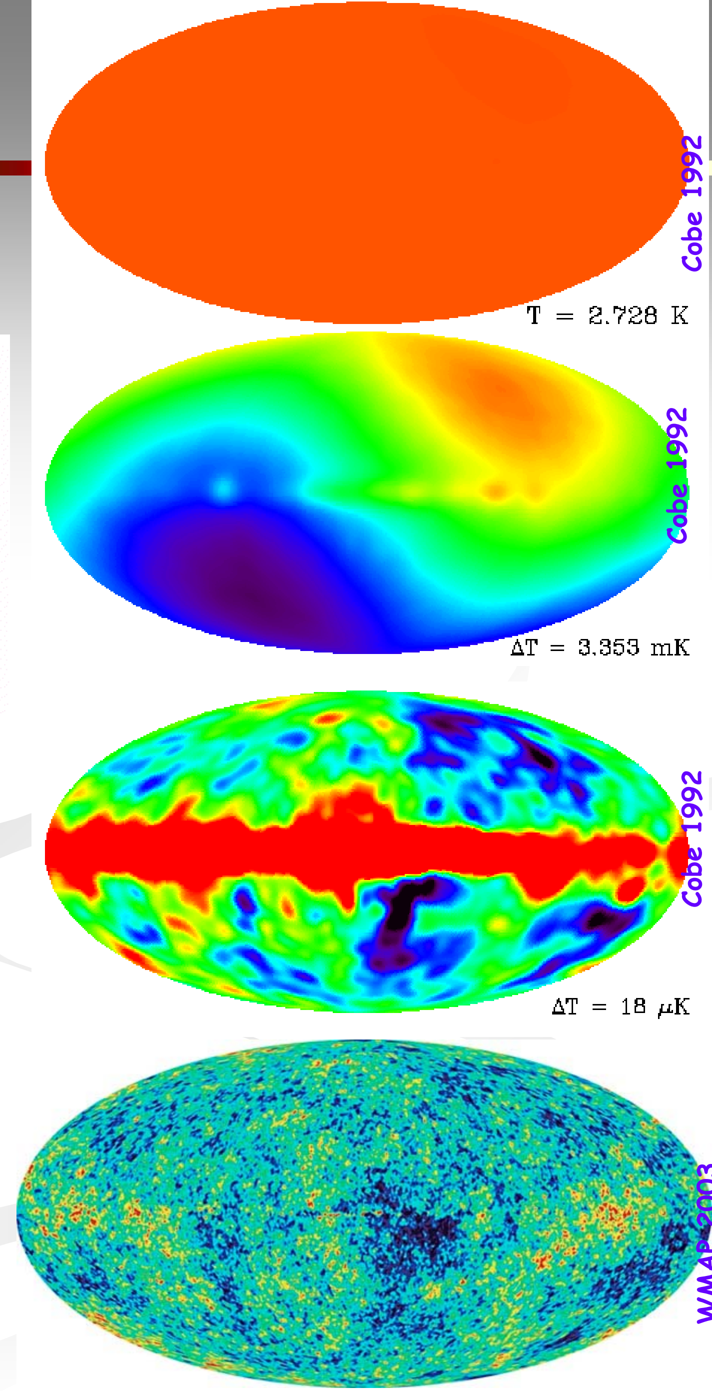
- CMB is a near perfect black body, 2.7° K
  (ℓ=0 monopole)



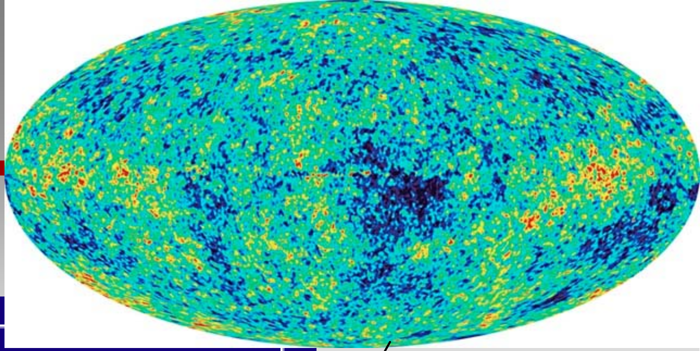
- Dipole Anisotropy 10^{-3}
  (ℓ=1 dipole)

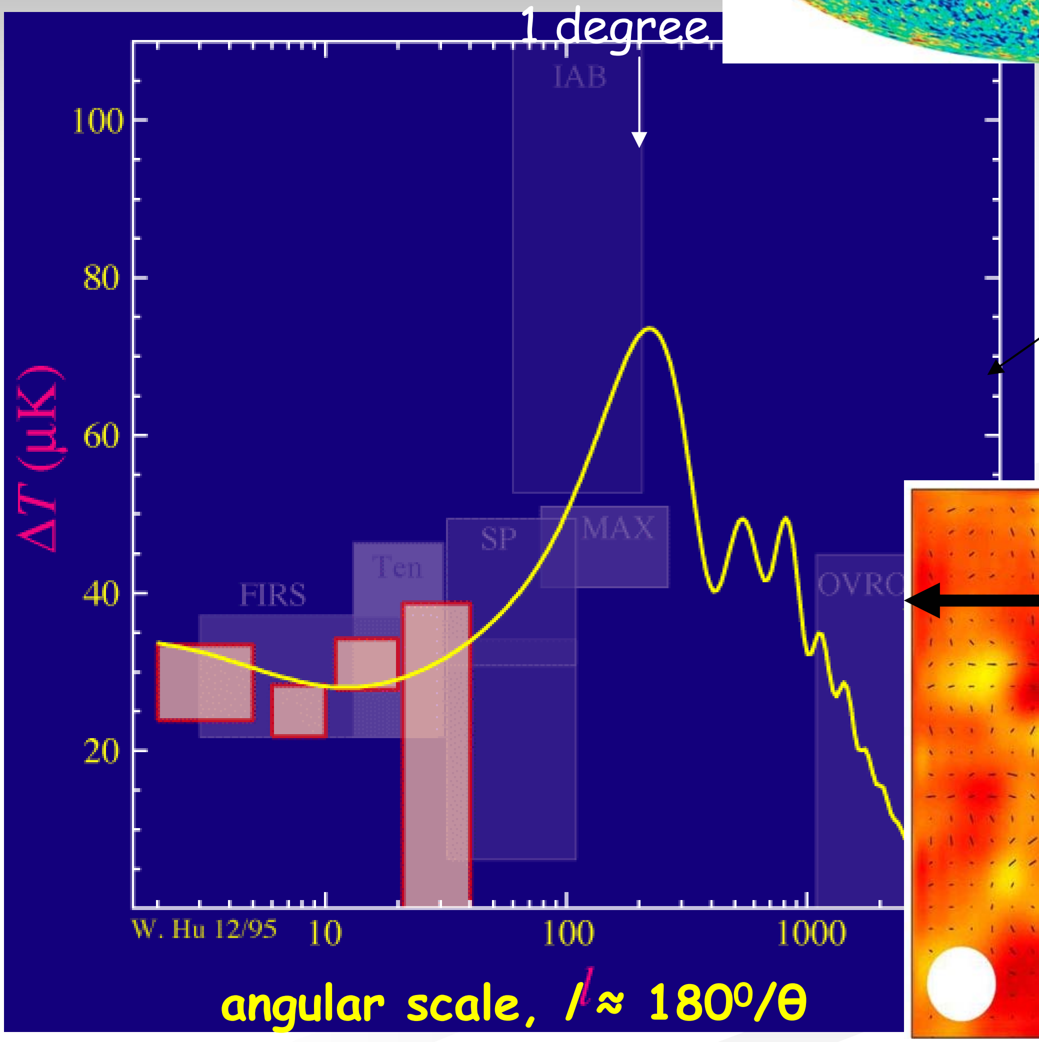
  (our motion in the CMB `rest frame')

- Temperature Anisotropy 10^{-5}



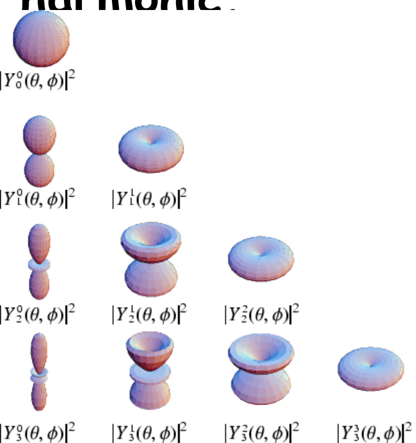
The Power Spectrum



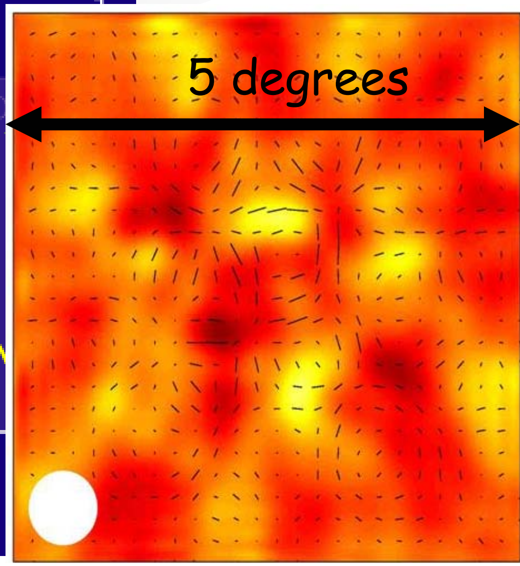


blotchy-ness of the sky at a particular scale

or…
how much the sky looks like a particular spherical harmonic.

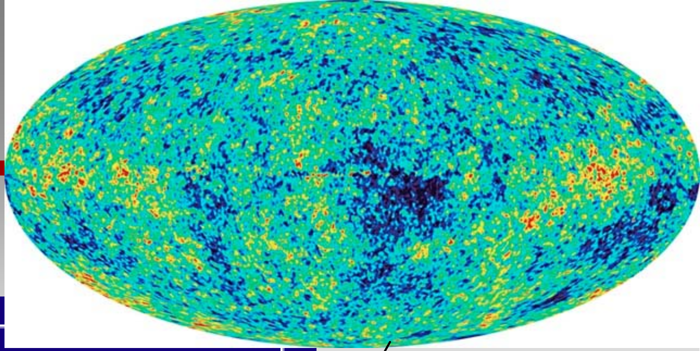


Gaussian fluctuations
→all stat. info is contained in the C_l's.

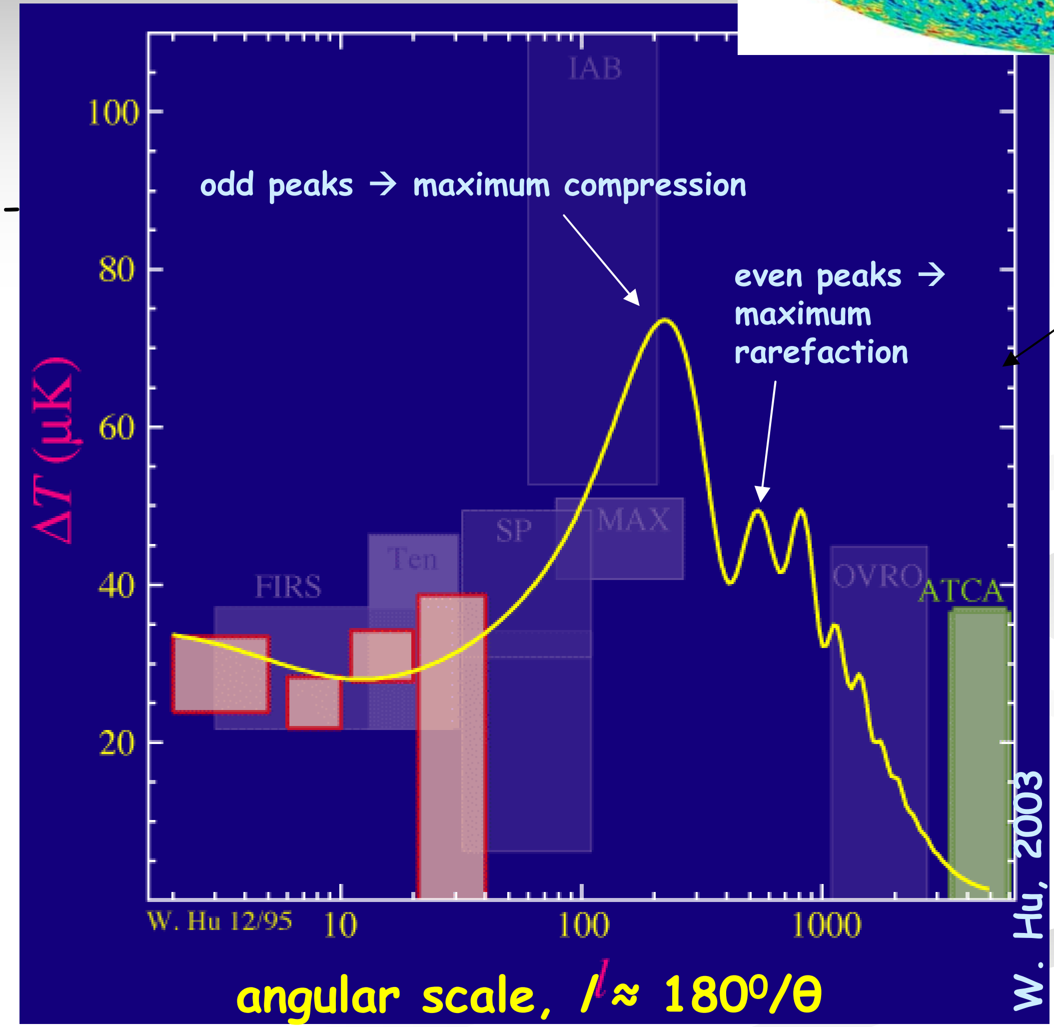


smaller scales

The Power Spectrum



Harmonic peaks
→ extrema in photon-baryon fluid oscillation cycle.



smaller scales

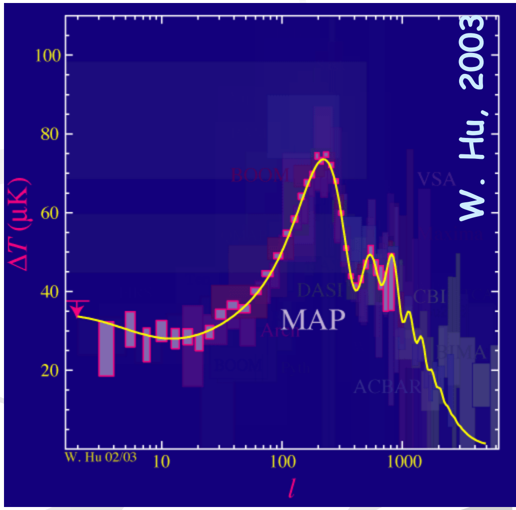
Measuring the CMB Temperature

- basic observable: intensity as a function of frequency and position
- for the temperature field,
  - (assume Gaussian fluctuations)

$$\Theta(\hat{n}) = \frac{\Delta T}{T} \quad \text{temperature fluctuations}$$

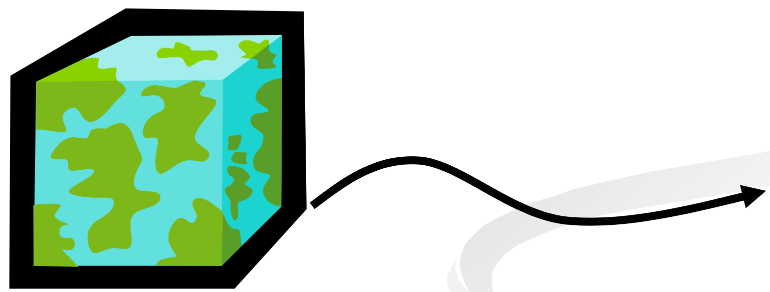
$$\Theta_{lm} = \int d\hat{n} Y_{lm}^{*}(\hat{n})\Theta(\hat{n}) \quad \text{multipole moments}$$

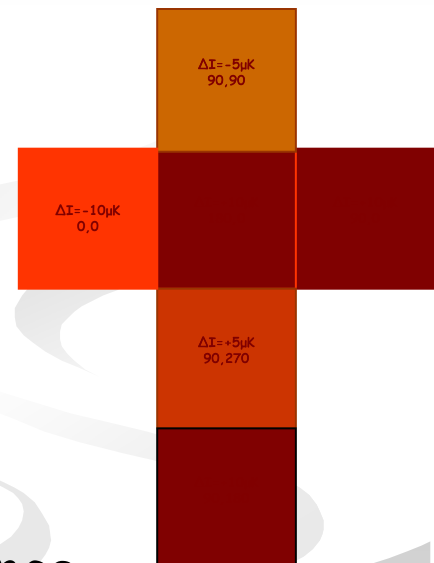
$$\langle \Theta_{lm}^{*} \Theta_{l'm'} \rangle = \delta_{ll'}\delta_{mm'}C_l \quad \text{power spectrum}$$



  - neglecting sky curvature, this reduces to a 2d-Fourier analysis.

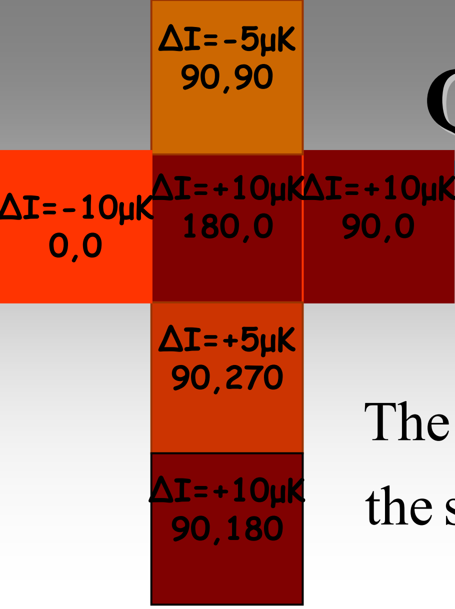
- Consider a toy experiment with 90^0 beams (watch glass primary)
- no polarization sensitivity (yet)
- full sky coverage.
- We divide the sky into a cubic surface with 6 pixels, which we look out on from the inside:





- if the universe has spots that are smaller than 90^0, we can't resolve them.
- But hey!, times are tough, so we go after the best science we can, and try to observe the lower l moments of the T anisotropy.

Quadrupole component of Power Spectrum

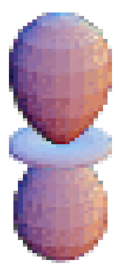


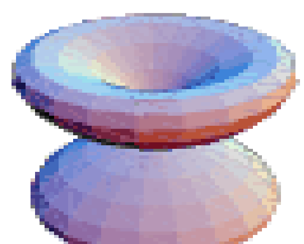
Our pixels are:
$n=(\theta,\Phi)$ = 0, 0
= 90, 0
= 90, 90
= 90, 180
= 90, 270
=180, 0

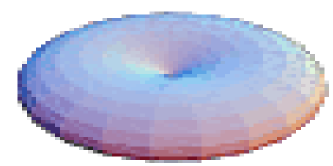
$$\Theta(\hat{n}) = \frac{\Delta T}{T}$$

The (complex) multipole moments quantify the extent to which the sky looks like the spherical harmonics :

$$\Theta_{lm} = \int d\hat{n}\ {}_{s=0}Y_{lm}^{*}(\hat{n})\,\Theta(\hat{n}) \overset{l=2,m=0}{=} \sum_{i=pixel} \frac{1}{2}\sqrt{\frac{5}{4\pi}}(3\cos^2\theta_i - 1)\bullet\frac{\Delta T_i}{T}$$







$|Y_2^0(\theta,\phi)|^2$ $|Y_2^1$

which we normally report in

$$\sqrt{\frac{l(l+1)C_l T^2}{2\pi}} = 62\,\mu K.$$

Why this funny normalization?

Power per log interval in l

$C_l \propto 2l+1$ (since $m = -l,\ldots 0,\ldots +l$)

and the variance

$$= \int d^2 l\, \frac{C_l}{(2\pi)^2} = \int dl\, \frac{c \bullet 2l+1}{2\pi} = \frac{c \bullet l^2 + l}{2\pi} = \frac{l(l+1)}{2\pi} C_l$$

we've made some simplifications…

A field of physics cows

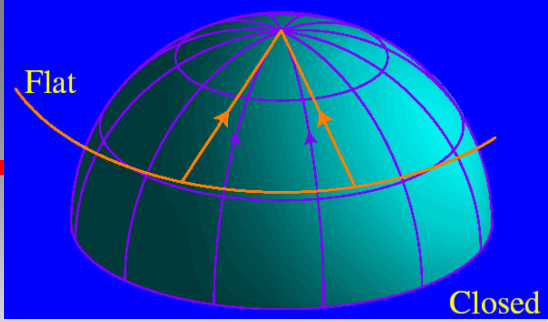
©2001 Drew Ness

- would need to de-convolute with beam shape functions, filter functions.
- measure and account for noise

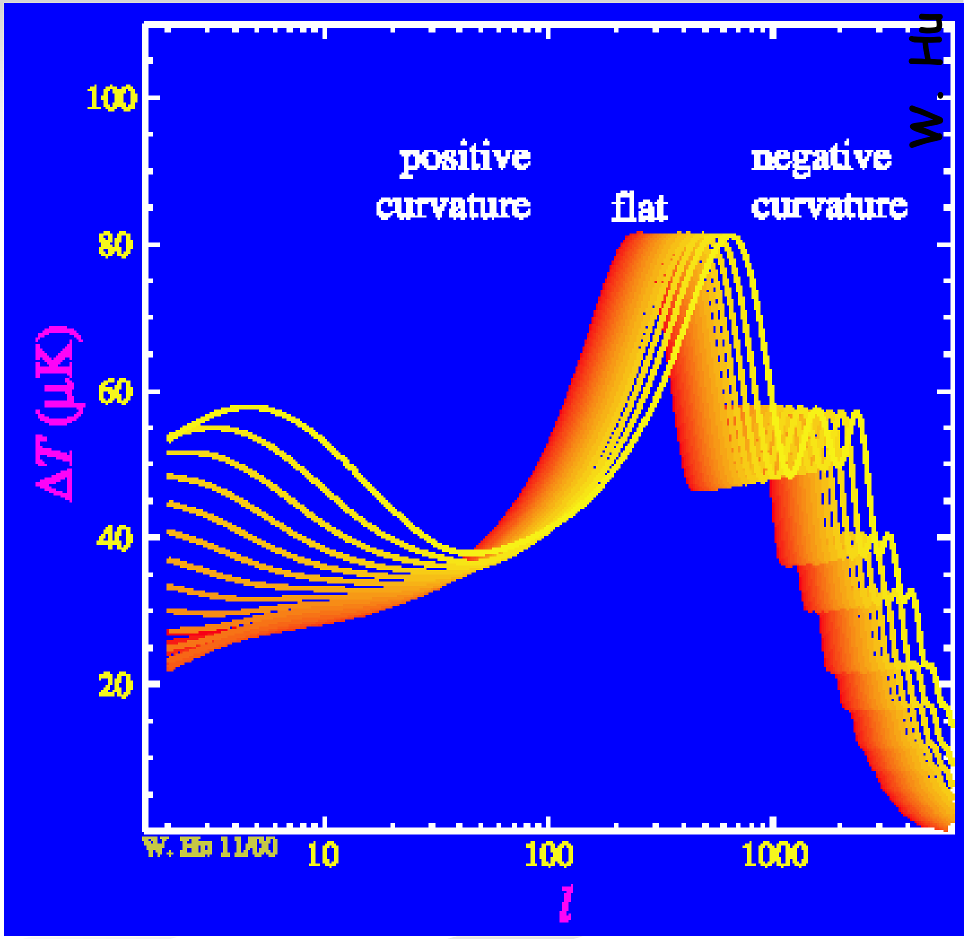
  typically filter some portion of it out of the timestream
  - correlated noise is a big pain.

→ deriving the answer isn't difficult,.. but the computations typically go as (number of pixels)^3, leading to computational problems/approximations

Curvature of Spacetime

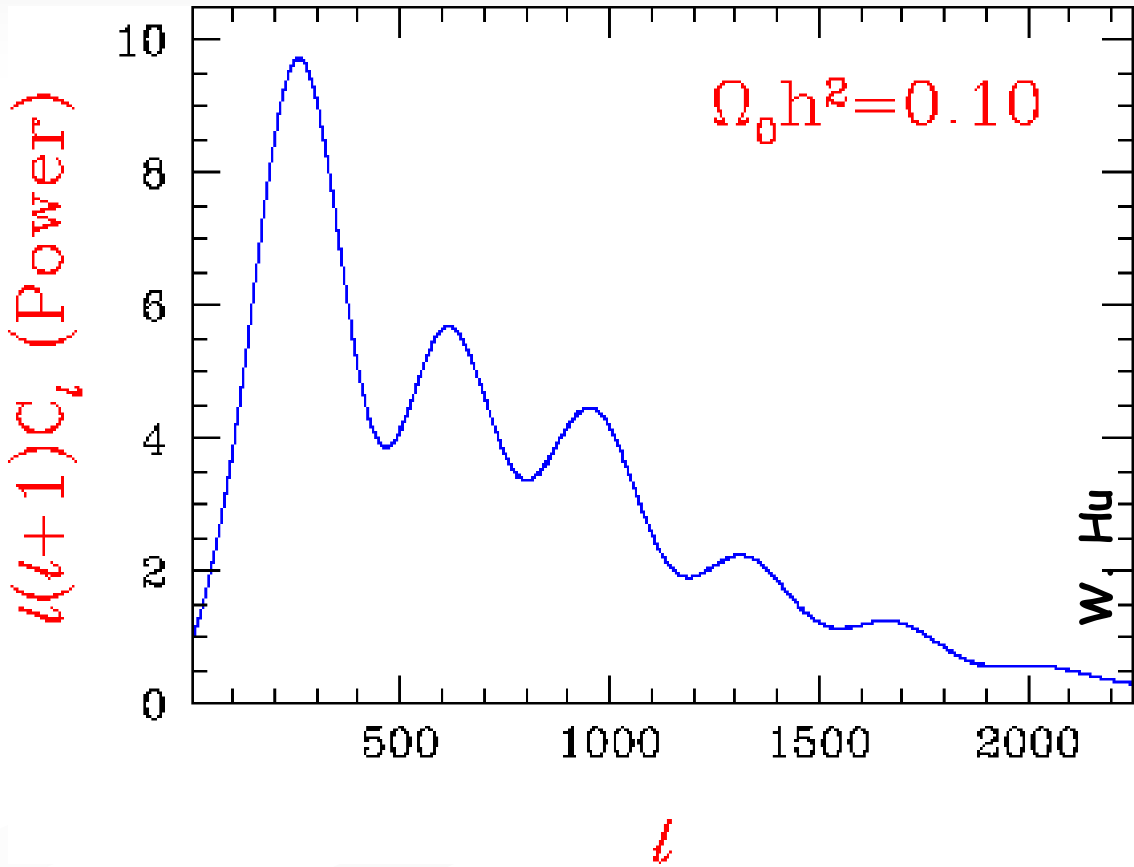


- The angular location of the first peak measures the curvature of spacetime, $\Omega_{tot}=1$.
  - effectively measures if anisotropies travel straight out to us along curved paths.



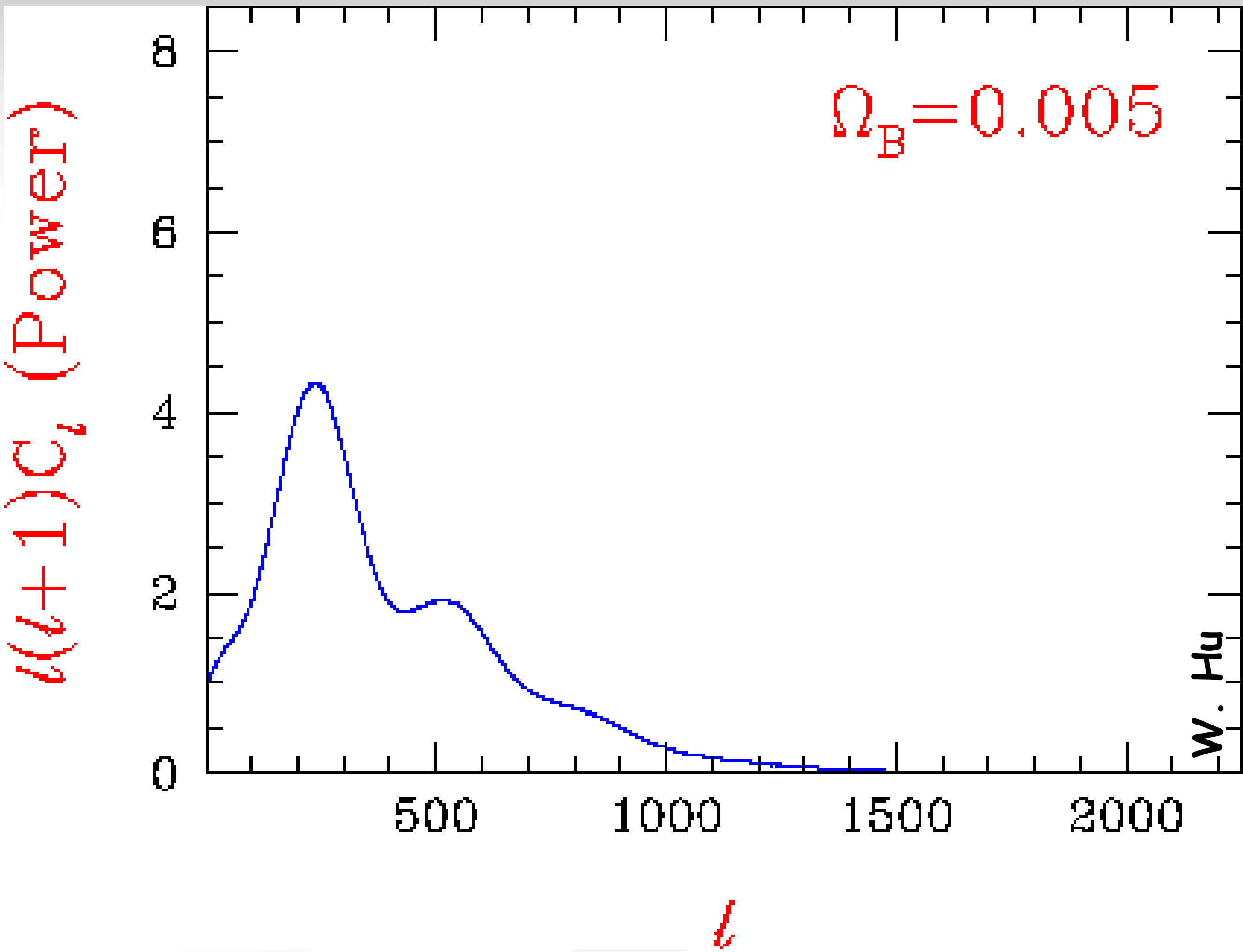
Power Spectrum: Ω_M

- total matter density
  $\Omega_M = \Omega_b + \Omega_{CDM}$
  determines the normalization of the power spectrum.

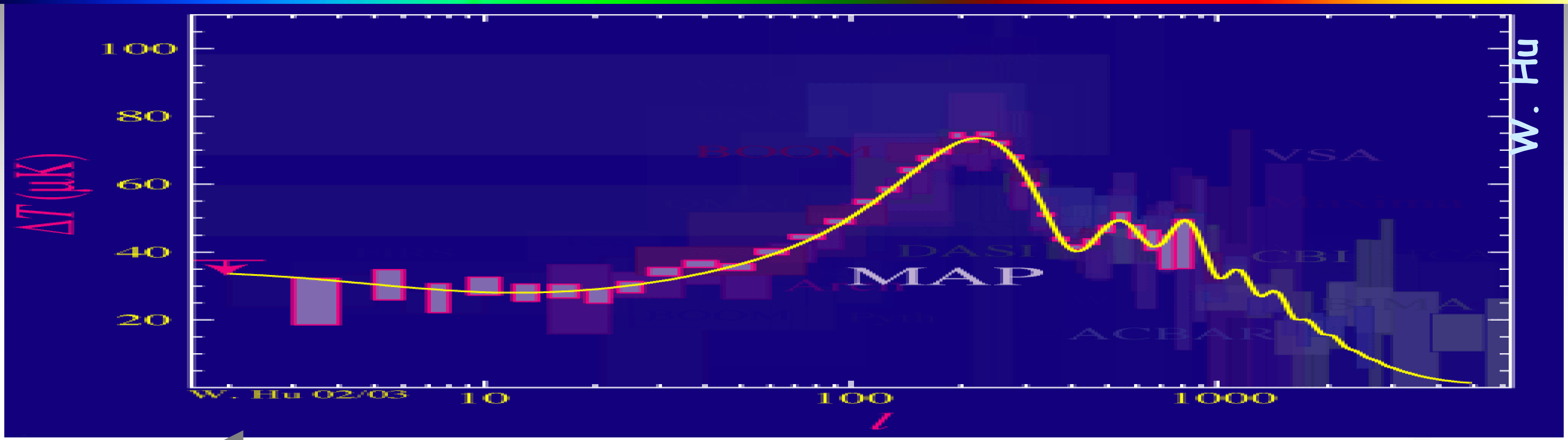


Power Spectrum: Ω_b

- ratio of 1st to 2nd peaks tells us the baryon content of the universe.
- enhances compression (odd) harmonic peaks.



What drives the errors?



Low l fundamental limitation is set by ***Cosmic Variance***.
There is only one sky and only 2 l +1 samples from the sky in each mulitpole moment.
Leads to an inevitable error

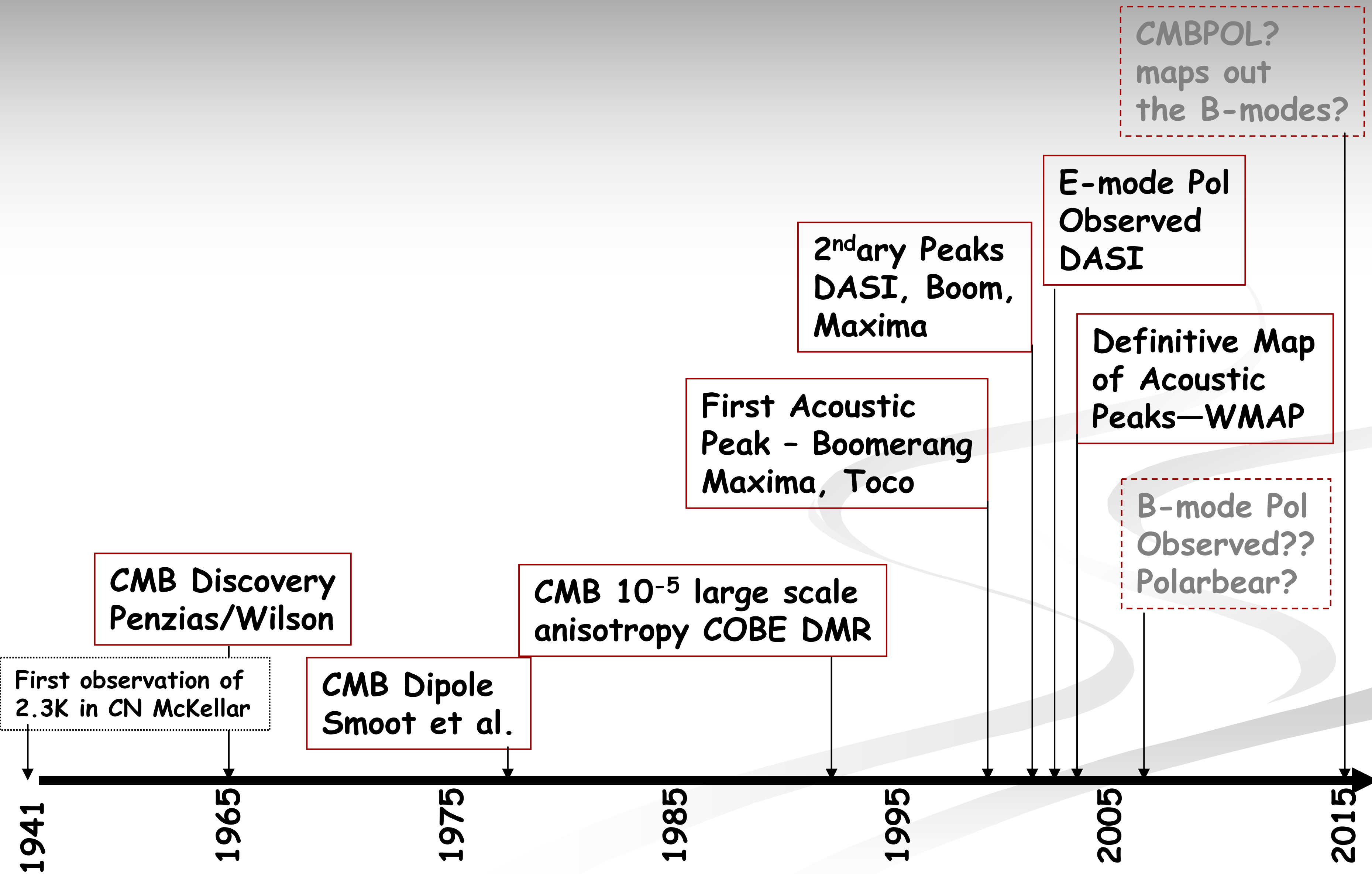
$$\Delta C_l = \sqrt{\frac{2}{2l+1}} C_l$$

(further improvement by binning, $\Delta l \sim l$)
Example: WMAP is cosmic variance limited for l <354.

If we survey a fraction f_{sky} less than the full sky, ***sample variance*** increases the errors by $1/\sqrt{f_{sky}}$. (Planck f_{sky}=.65)

At high l, approaching the experiment resolution scale, noise (photon stats, electronics, astrophysical) dominate.

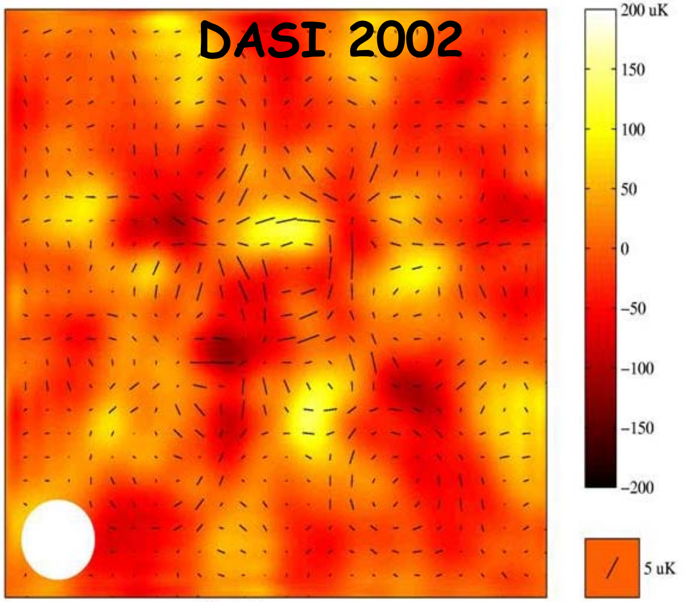
CMB Observations



Why measure CMB Polarization?

- scalar, vector & tensor fields carry more information than the temperature anisotropies alone.
- gives us more information about the acoustic peaks

→ measure cosmo parameters better



Map is 5 degrees square

- measure the reionization epoch, which produces a large degeneracy in the Temp spectrum
- measure gravity wave amplitude… the smoking gun of inflationary models.

Thomson Scattering & Polarization

- Incoming polarized light emerges polarized.

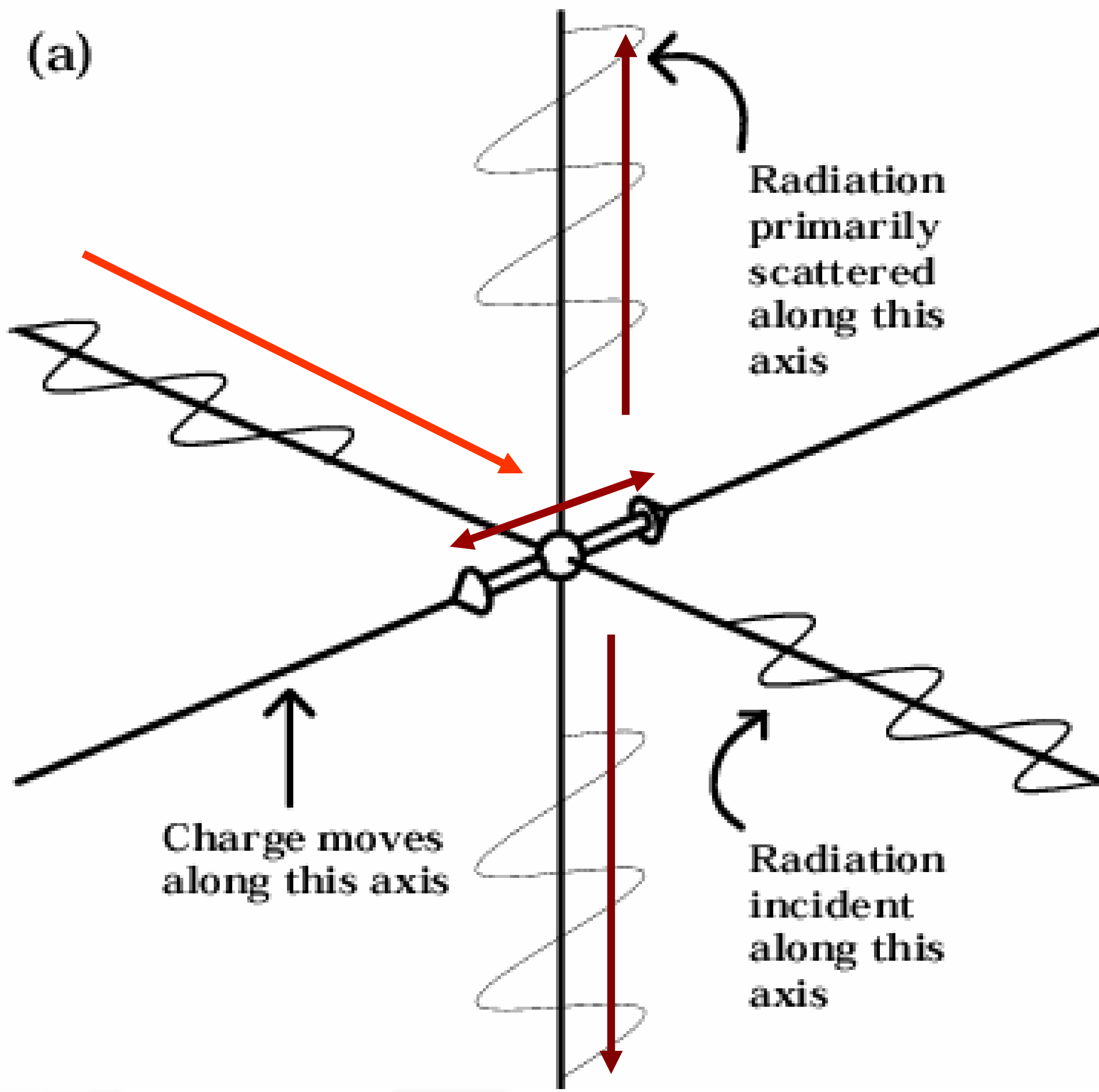


Figure: M. Hedman PhD Thesis.

Thomson Scattering & Polarization

- A plane wave undergoing Thomson scattering produces polarized light too.
- but if we have equal amounts of light coming from all directions, there is no net polarization.

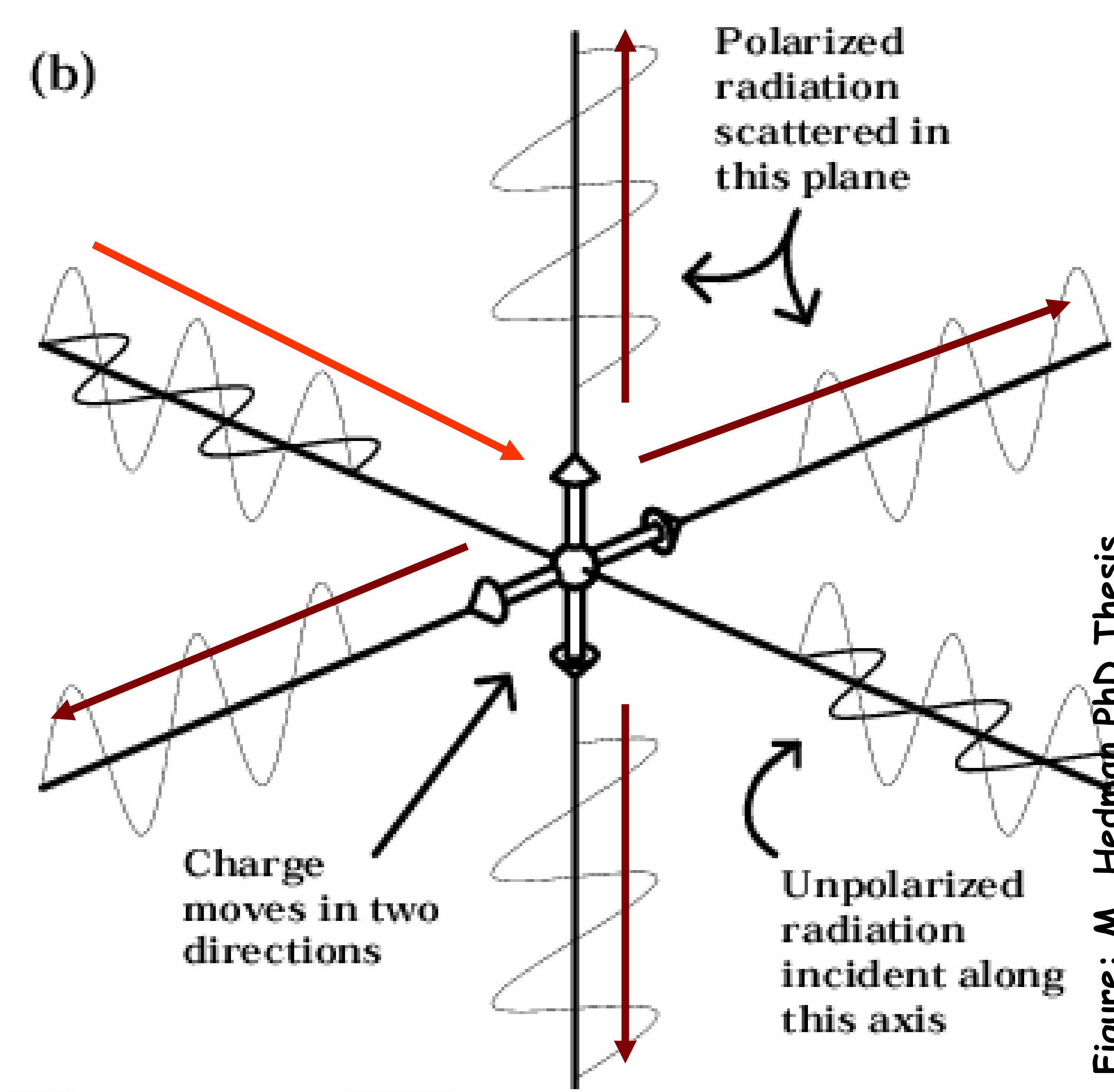


Figure: M. Hedman PhD Thesis.

Thomson Scattering & Polarization

- Incoming polarized light emerges polarized.
- A plane wave undergoing Thomson scattering produces polarized light too.
- but if we have equal amounts of light coming from all directions, there is no net polarization.
- but if different intensities of quadrupole (unpolarized) light arrive from different directions, the net result is polarization. (10% of ΔT)

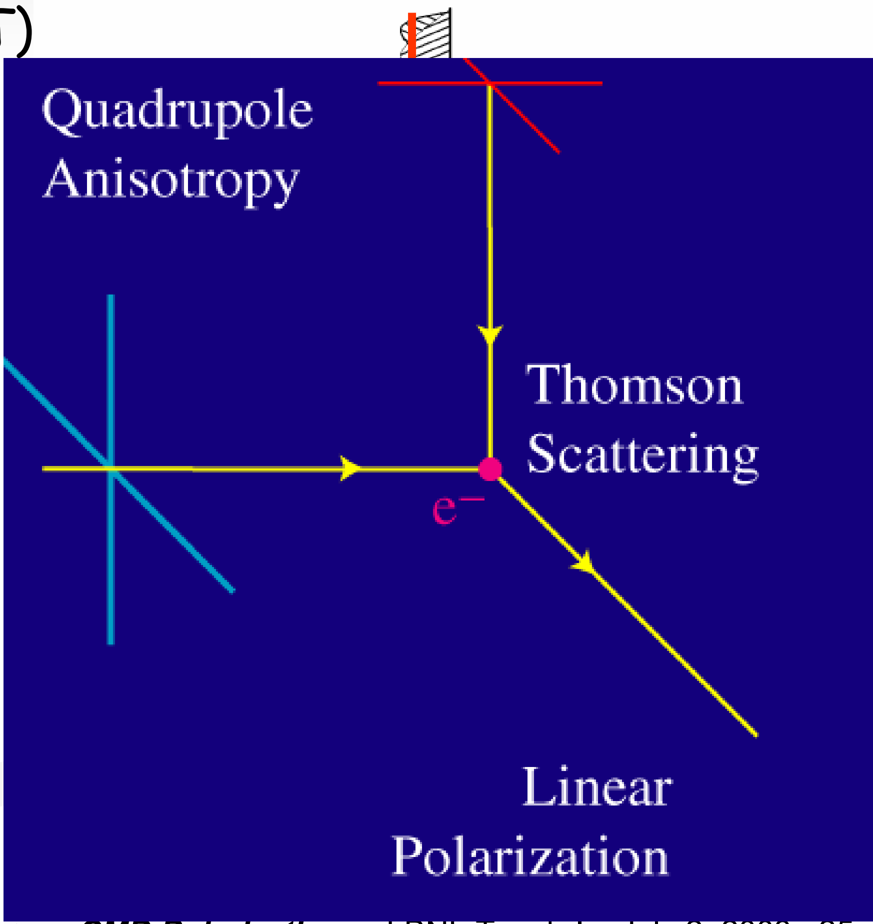


Figure: W. Hu doctored by G. Smoot

Polarized Light & Stokes Parameters

- Stokes vector $S=(I,Q,U,V)$ describes the intensity and polarization of light.

$$\cancel{V \equiv I_{RCP} - I_{LCP}}$$

absent in cosmo setting

$$U \equiv I_{+45} - I_{-45}$$

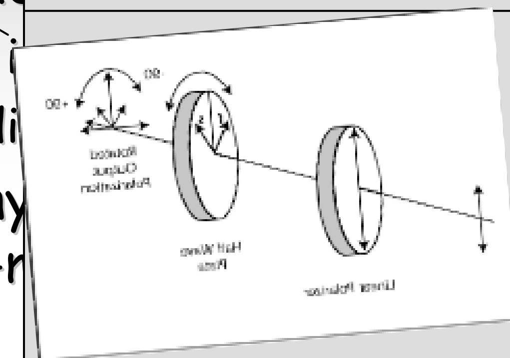
$$Q \equiv I_0 - I_{90}$$

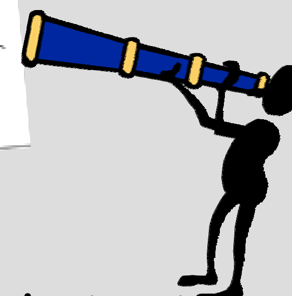
$I \equiv$ total intensity

- Think of Q as the "preference" of the light for horizontally (Q=+1) polarized light.
- For unpolarized light Q,U,V are all zero. For polarized light, $Q^2+U^2+V^2=1$.

Polarized Light

- Basic observable: intensity and polarization as a function of ν and n, S=(I,Q,U,V)=S(ν,n)
- We can divide the sky up into pixe ... el
  - circular polarization, V is absent i
  - there is no E,B-mode info for indi
- By doing a vector analysis of many
  gradient ("E-mode") and curl ("B-r

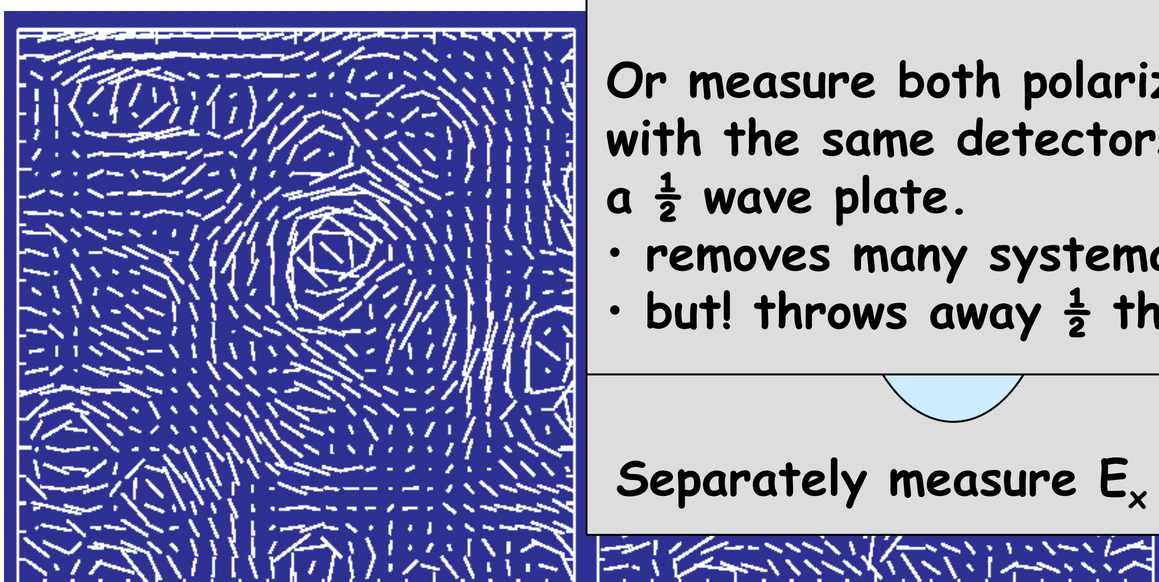




Or measure both polarizations with the same detectors using a ½ wave plate.
• removes many systematics
• but! throws away ½ the light.

Separately measure E_x and E_y.

vector field
E (grad) mode
polarization

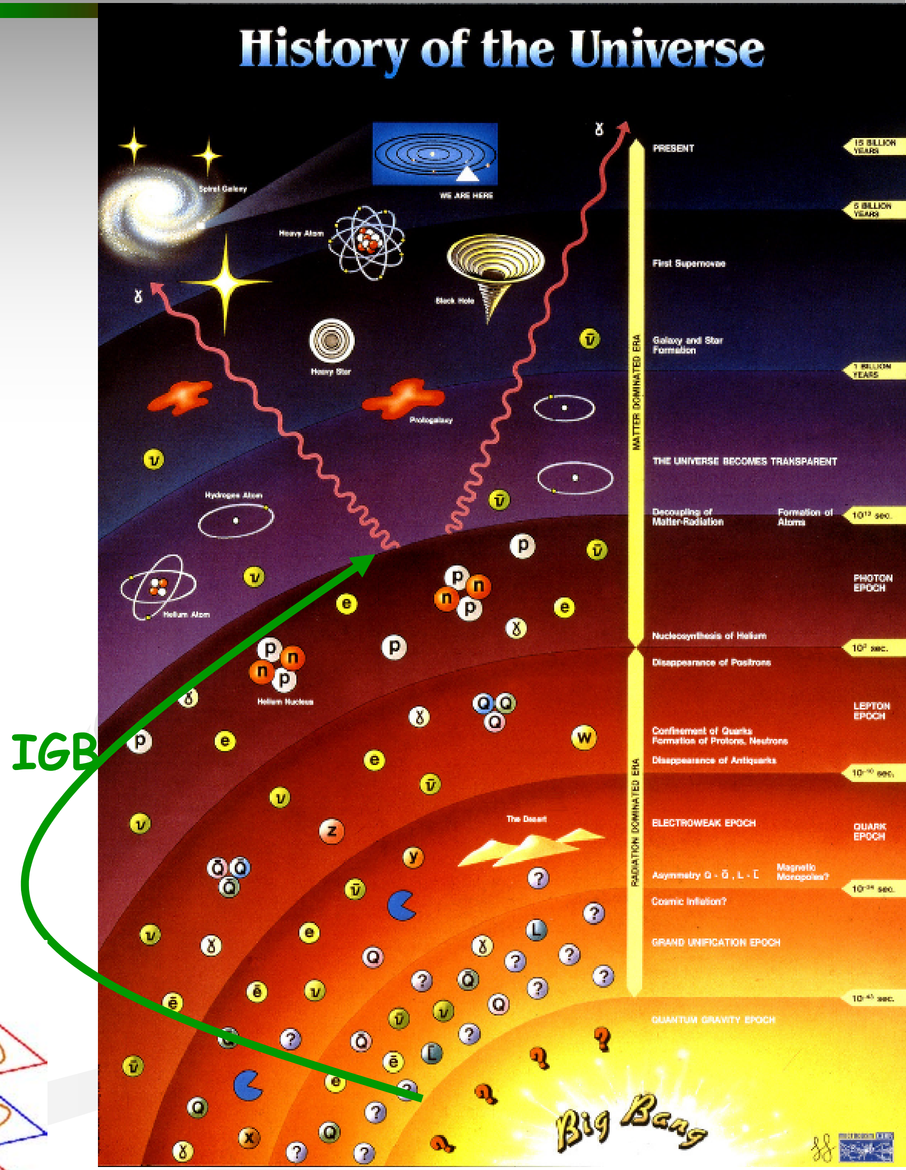


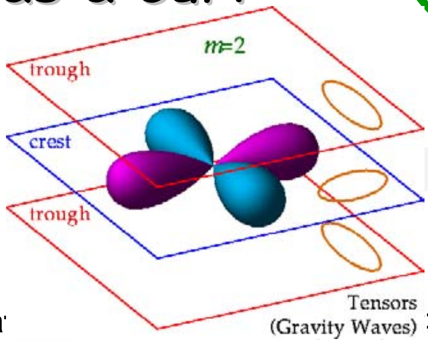
eld
ode
on

w.

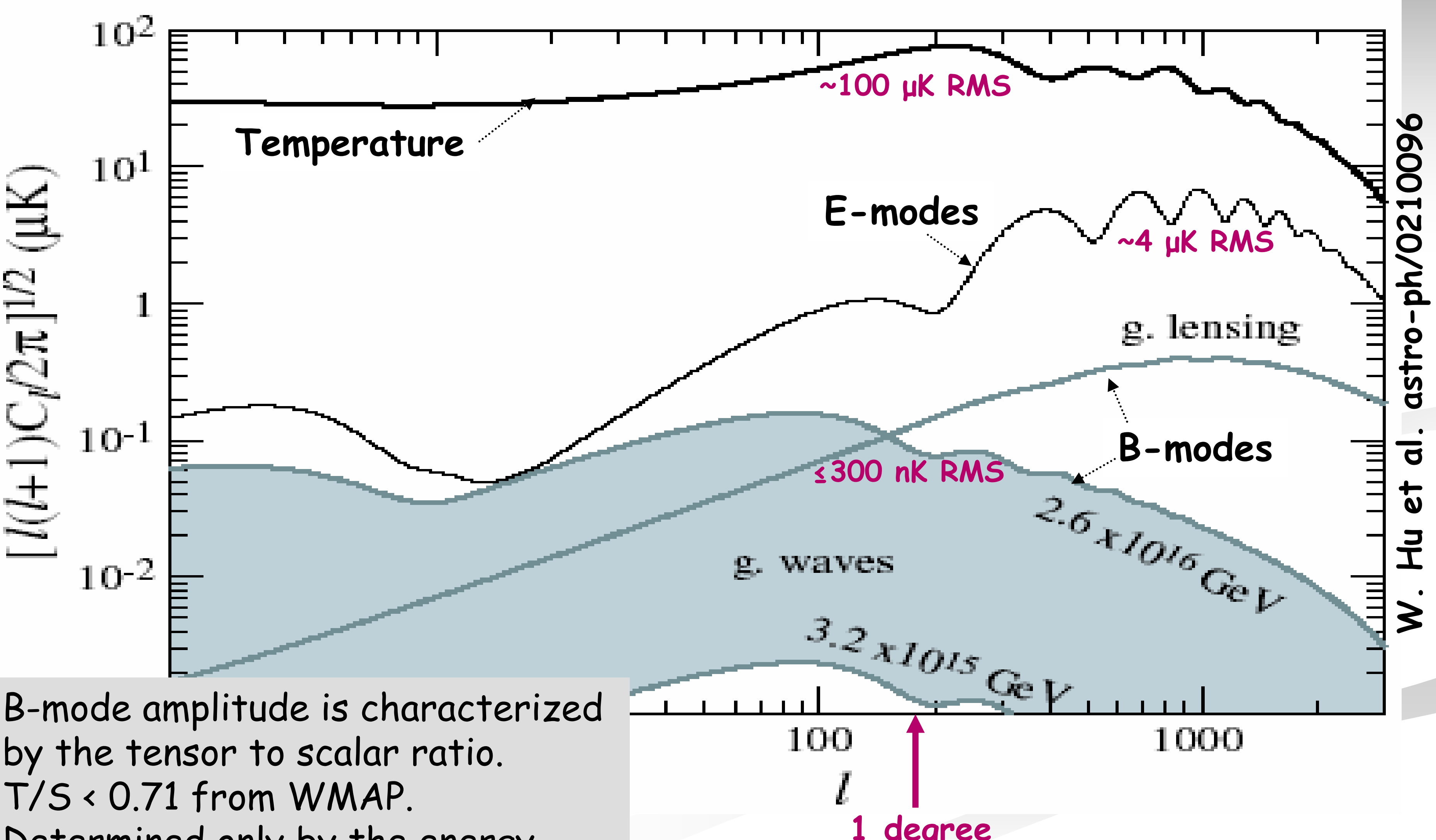
B (curl)-mode Polarization

- Just as the CMB gives the fingerprint of the universe at t=400 Kyears,
- the fingerprint at the time of inflation (10^{-38}, ? s) is encoded on the ***inflationary gravity wave background*** (IGB).
- This gravity wave fingerprint stretches and compresses spacetime on the surface of last scattering—transmitting that information as a curl component in the polarization.





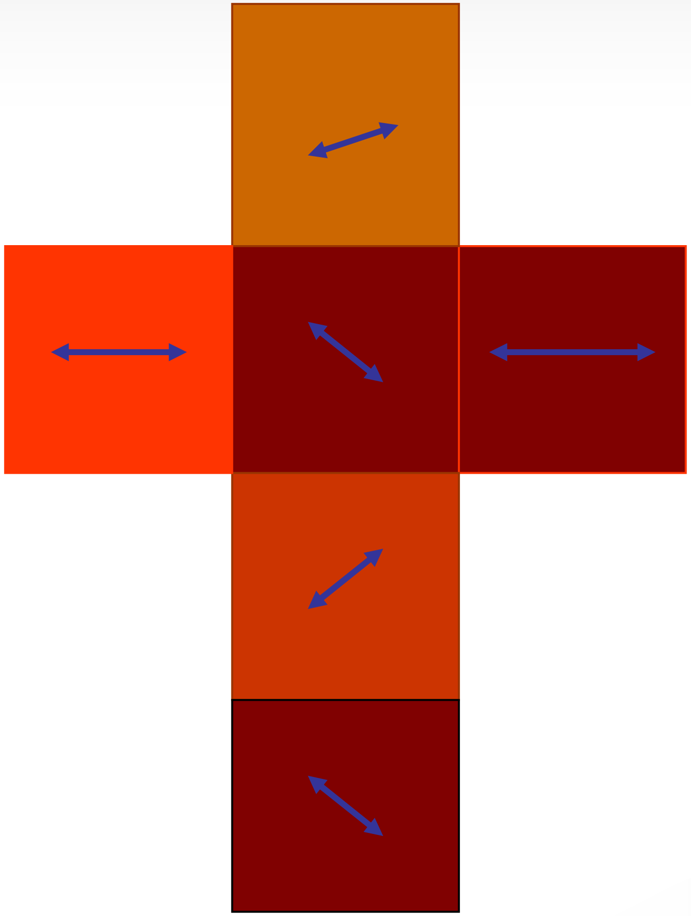
Polarization Power Spectrum

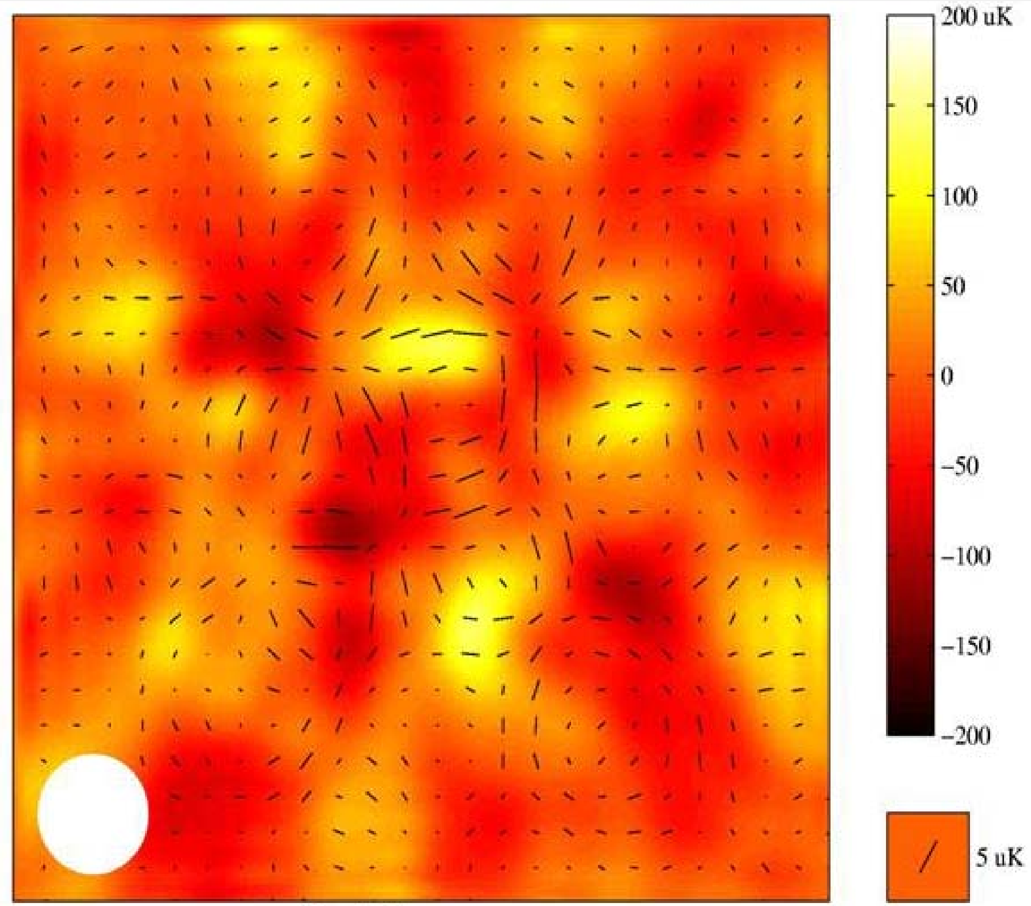


B-mode amplitude is characterized by the tensor to scalar ratio.
T/S < 0.71 from WMAP.
Determined only by the energy scale of inflation.

Polarization Sensitive MAP

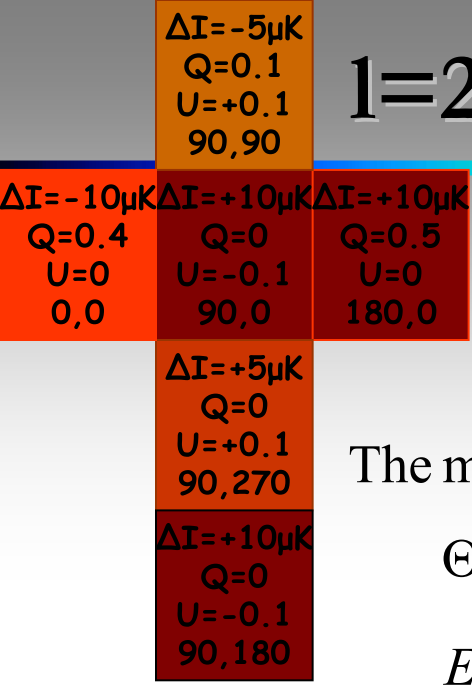
- we upgraded our toy experiment to be polarization sensitive.
- For each pixel we measure I,Q,U Stokes parameters, and obtain a map like:





Map is 5 degrees square

l=2 moment of Polarization Spectrum



$$\Theta(\hat{n}),\, Q(\hat{n}), U(\hat{n})$$

The multipole moments are:

$$\Theta_{lm} = \int d\hat{n} \;\; {}_{s=0}Y_{lm}^{\;*}(\hat{n})\, \Theta(\hat{n})$$

$$E_{lm} \pm iB_{lm} = -\int d\hat{n} \;\; {}_{s=2}Y_{lm}^{\;*}(\hat{n}) \left[Q(\hat{n}) \pm iU(\hat{n})\right]$$

and we have used the spin-weighted spherical harmonics

$$i.e. \quad {}_{s=0}Y_{2,0}(\hat{n}) = \frac{1}{2}\sqrt{\frac{5}{4\pi}}(3\cos^2\theta_i - 1) \rightarrow {}_{s=2}Y_{2,0}(\hat{n}) = \frac{3}{4}\sqrt{\frac{5}{6\pi}}(\sin^2\theta_i)$$

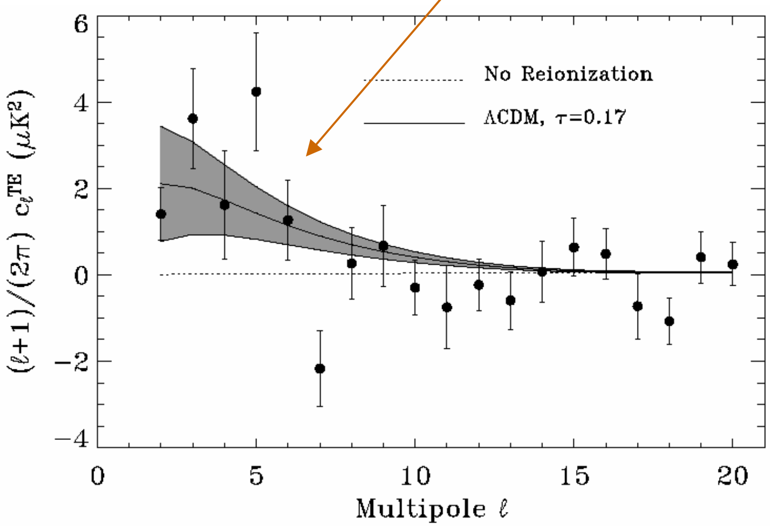
and our two point correlation functions are:

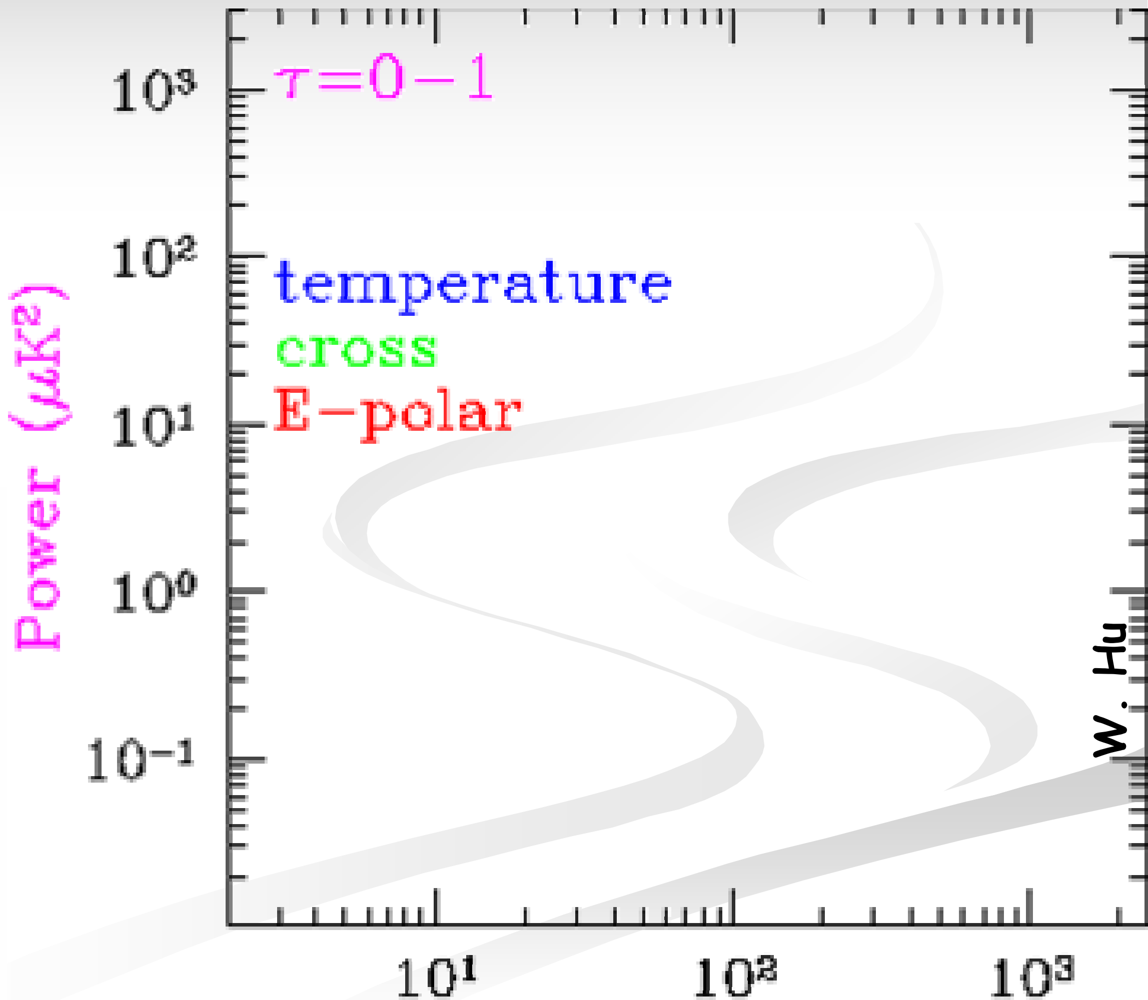
$\left\langle X_{lm}^{\;*} X'_{l'm'} \right\rangle = \delta_{ll'}\delta_{mm'}\, C_l^{XX'}$ providing power spectra $C_l^{\Theta\Theta'}, C_l^{\Theta E'}, C_l^{EE'}, C_l^{BB'}$.

($C_l^{BX'}$ with $X' \neq B$ is zero if parity is conserved).

Reionization

- In the temperature $C_l^{\theta\theta}$ there is a degeneracy between reionization, and the overall normalization.
- This degeneracy is broken by the polarization fields.
  - Measured by WMAP τ=0.017±0.04





(a few of) The Polarization Experiments

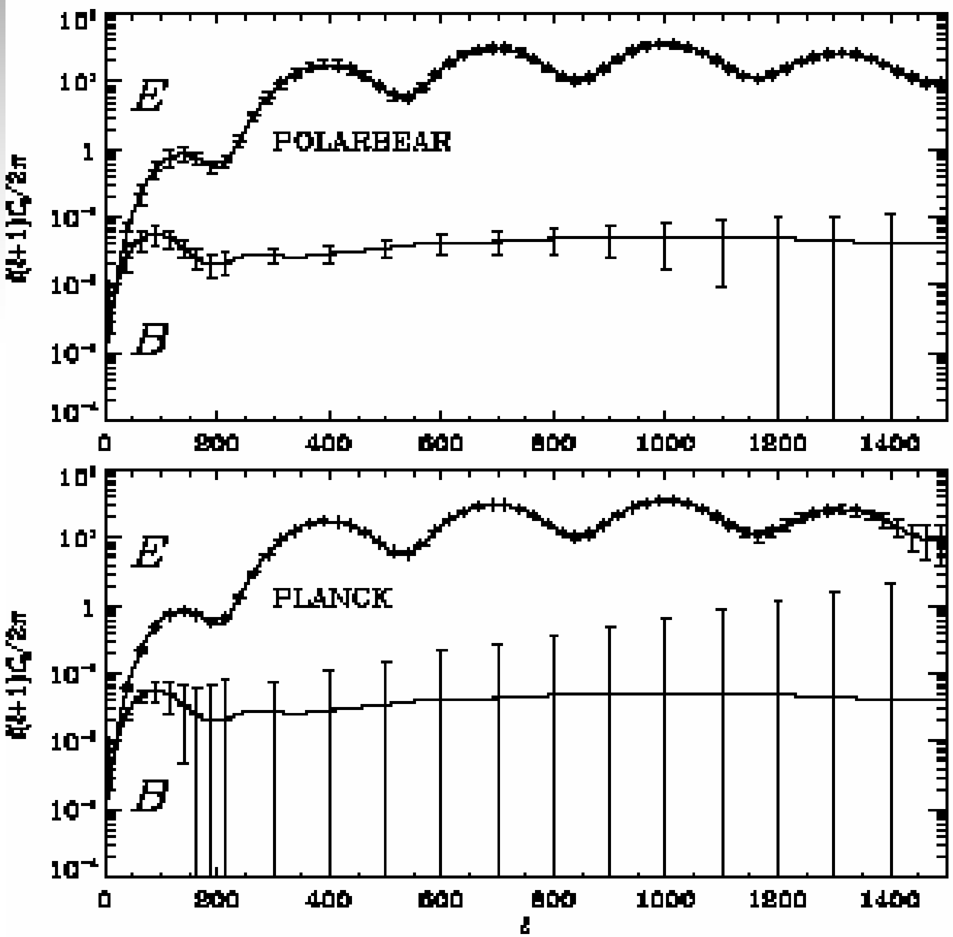
now

- DASI (interferometer at the South Pole)
  - first observation of E-mode polarization 2002
- Boomerang / MAXIPOL Balloon based telescopes
  - E-mode observations
- WMAP NASA Satellite 2001-5
  - $C^{\Theta E}_{l}$ measured, → low l bump consistent w/ reionization
  - E-mode spectrum expected. B mode reach is small.
- Bicep (South Pole 2004/5)
  - E-mode polarization on large angular scales, B-mode discovery potential
- POLARBEAR (California 2005-) 3m ground based telescope
  - characterize E-modes, discover B-modes
  - facility for testing satellite technology
- Planck ESA/NASA Satellite (2007-)
  - characterize E-modes, discovery potential for B-modes
- CMBPOL Einstein Probe Satellite (2013/16)
  - definitive measurements of E-mode, significant B-mode reach

Ground based: POLARBEAR

- LBNL/UCB project (proposed)
  - first light 2005 from White Mtn with a ~3m primary.
    - atmospheric emission is nearly unpolarized.
    - large sky coverage for primordial gravity waves
    - sufficient resolution to measure and subtract out gravitational lensing signal.
    - staged deployment – 300 elements, upgrade to fMUX 1000s of elements.
    - multi-frequency polarization sensitive antenna coupled toTransition Edge Sensor bolometers
- testing facility for future satellite technologies, systematics, and foreground measurements.

POLARBEAR Performance



3 years observing
(Assuming a Tensor to Scalar ratio r=T/S=0.35)

3 yrs x 25% duty
➔ 200 nK/pixel on 10 x 10 deg^2

Sensitivity:
Polarbear I r=T/S > 0.02
Polarbear II r=T/S > 0.0005

… but understanding systematics and foregrounds are the biggest challenges now →

Polarization Systematics

- instrument polarization I ➔ Q,U
  - smooth term $\delta T_l \rightarrow \delta E_l, \delta B_l$ angle dependent term $\delta T_{l'} \rightarrow \delta E_l, \delta B_l$
  - fixed in the instruments coordinate system → optimize scan strategy.
- cross polarization Ex ←➔Ey Q←➔U
- polarization efficiency (i.e. does polarized light get depolarized or lost) Q,U → I
- polarization conversion Q/U ➔ signal

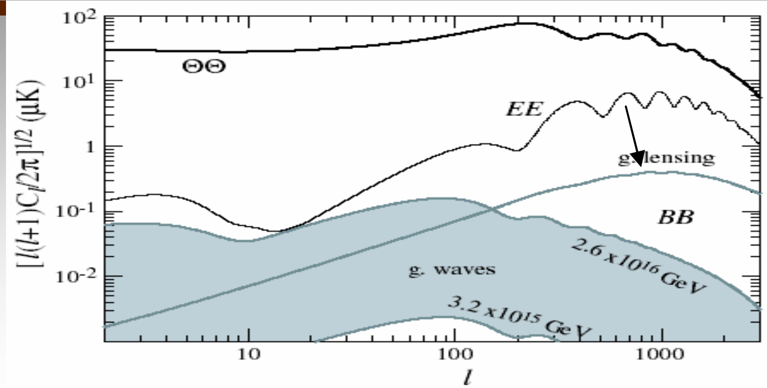
Our Toolkit:

- Multiple levels of differencing:
  - subtraction of orthogonal antennas
  - modulate polarization w/ half wave plate, etc.
  - scan strategy, rotation of sky
- High SNR helpful – e.g. compare halves of the data.
- low side-lobe response telescope to avoid polarization from ground reflections, etc.

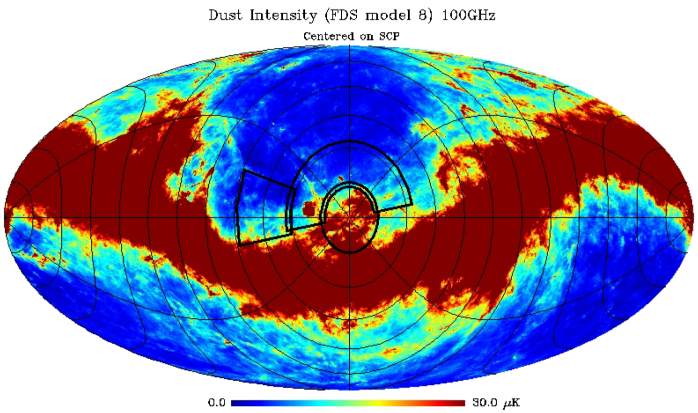
Could measure these effects with a known polarized sources and perfect unpolarized black body.

Polarization Foregrounds

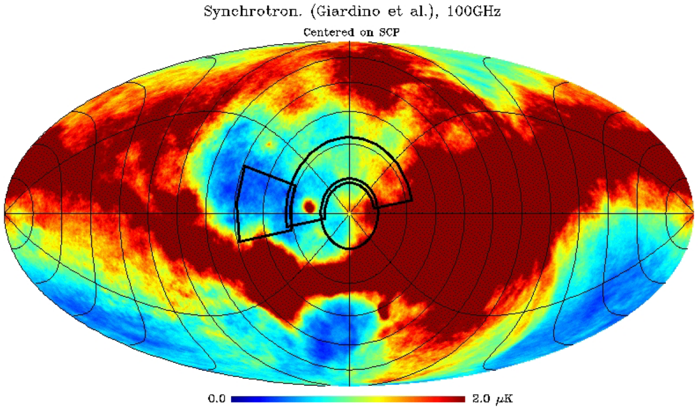
- Gravitational Lensing
  - converts E → B modes
  - → sufficient angular resolution (high l) is primary tool for subtracting out cosmic shear.



- Galactic dust
  - intensity is well known
  - polarization very poorly known



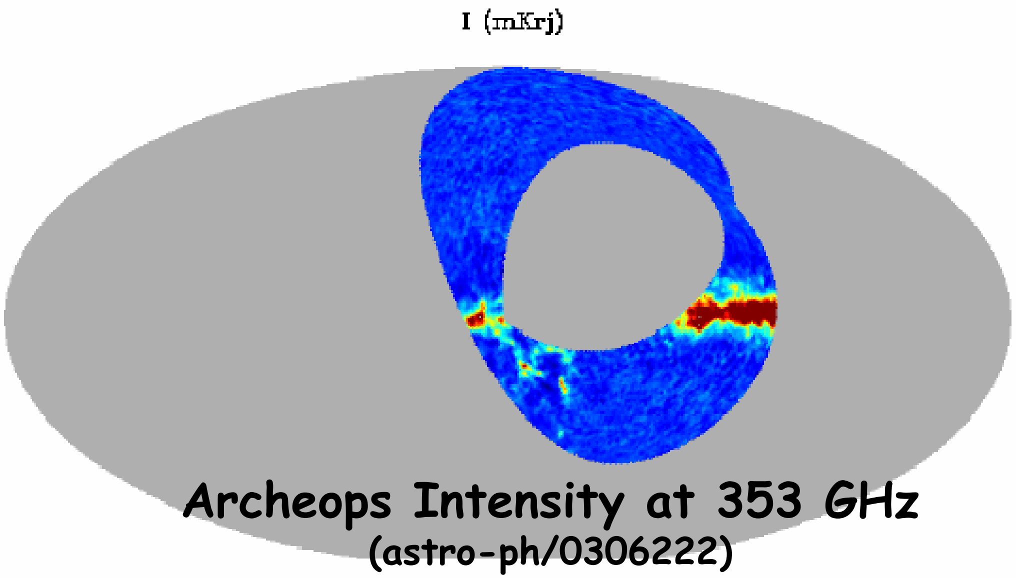
- Synchrotron Polarized Emission
  - must extrapolate data from 1-3 GHz up to 100 GHz.



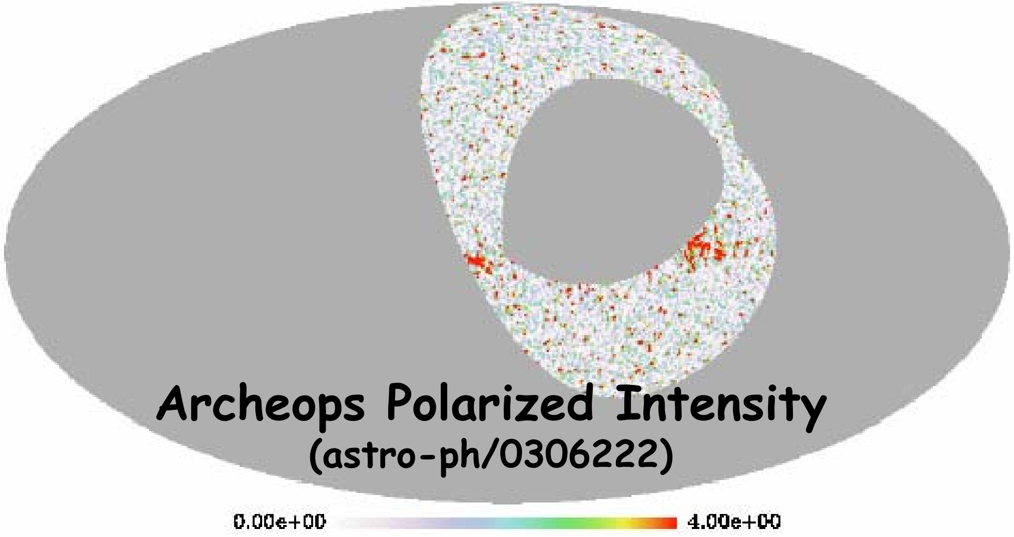
Polarized Galactic Dust Emission

- new results from Archeops (balloon flown over Sweden) provides first measurements of dust-pol on scales >10'
- Typically polarized at 4-5% level, can be as high as 10-20%.
- These maps look very different in different bands.

→ multiband observations are primary tool against dust-pol.

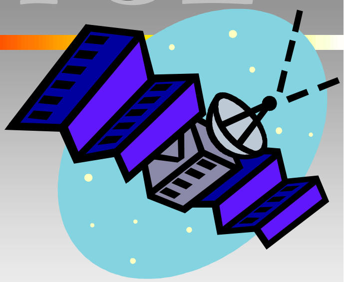


Archeops Intensity at 353 GHz
(astro-ph/0306222)



Archeops Polarized Intensity
(astro-ph/0306222)

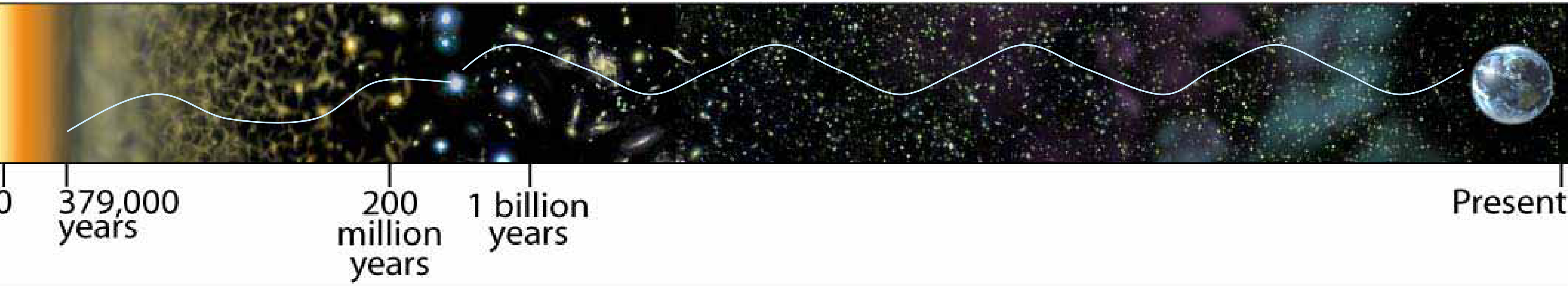
Einstein Probe Satellite: CMBPOL



- Proposals for concept studies submitted.
- 2013-16 launch with science goals
  - definitive measurement of E-mode polarization
    - cosmic variance limited all the way out to the damping tail.
  - detect B-mode polarization down to $E_{inflation}$ <~ 10^{15} GeV
    - sensitivity limited by residual astrophysical foregrounds
  - measure w equation of state with SZ, cosmic shear
  - measure sum of neutrino masses with cosmic shear

- expect polarization sensitivity of 1 μK s^{-1}
- lots of R&D between now and then- upcoming polarization facilities will be test-beds for CMBPOL instrumentation.
  - ....

more CMB science…

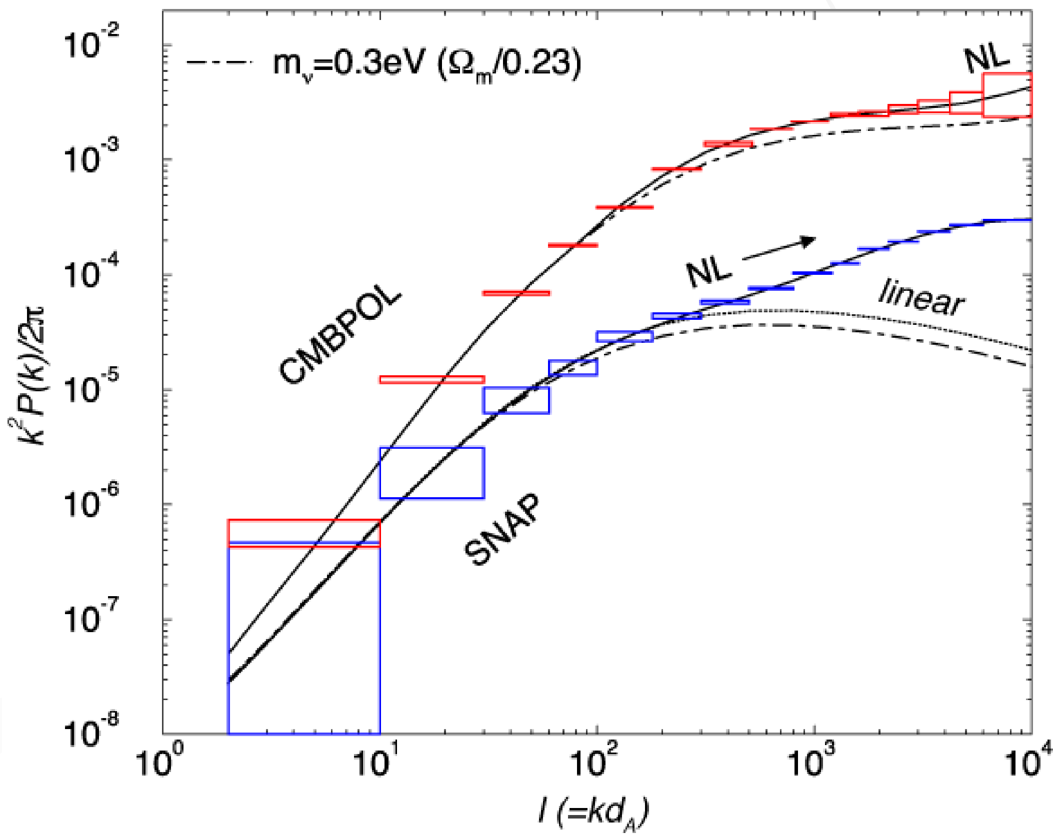


- CMB Secondaries– physics that happens after the primary anisotropy is encoded at the surface of last scattering.
- CMB photons are used to backlight structure in the universe that is newer than z~1100.
  - Cluster surveys with the Sunyaev Zeldovich effect $\rightarrow \Omega_M$, w
  - gravitational lensing
    - measurement of the neutrino mass
  - …

Grav. Lensing of CMB: Neutrino Mass

- power spectrum for cosmic shear of the CMB at small angular scales is sensitive to neutrino masses
  - measures the matter content (all matter!, not just luminous matter!) along the light of sight.
  - future CMBPOL satellite may have a sensitivity of ~0.03 eV.

Neutrino mass effects enter where linear perturbation theory applies… different from SNAP.



Conclusions

- E-mode polarization
  - significantly increases info about the cosmo parameters
  - removes the degeneracy from reionization
- B-mode polarization
  - tool for probing Inflationary Gravity Wave Background
  - secondaries provide equally exciting science: matter power spectrum, neutrino masses, cluster surveys
  - systematics and foregrounds are important
- new E-mode results expected soon
  - Boomerang, Maxipol, WMAP
- first significant B-mode measurements
  - will come from the ground, allowing easy modifications, to handle foregrounds and systematics– as they become known
  - This knowledge will be assembled to construct a CMB polarization satellite ~ 2015.

Resources for Further Study

- Wayne Hu's Webpage, http://background.uchicago.edu/~whu/
- Hu/Dodelson, *Ann. Rev. Astron. Astrophys.* **40** 171 (2002) astro-ph/0110414
- Hu/White, *A CMB Polarization Primer*, astro-ph/9706147.
- for HEP folks: Rubakov, *Cosmology and Astrophysics*, CERN Summer School, CERN-YR-2002-002.